Bulletin of the Seismological Society of America, Vol. 87, No. 4, pp. 782–787, August 1997

Propagational Corrections for Basin Structure: Landers Earthquake

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Abstract Transfer functions appropriate for correcting for propagational distortion caused by basin structures (2D) given a hard-rock (1D) response are developed. The transfer functions are generated theoretically using a hybrid method where the finite-difference technique is employed only in the basin. This allows for efficient computation and the ability to separate path contributions due to body waves and surface waves. The procedure is used to explain some strong motions observed in the Los Angeles basin relative to the hard-rock site Pasadena during the 1992 Landers earthquake.

Introduction

The analysis of long-period strong motions as observed in complex geological structures such as basins remains a difficult problem. While the propagational complexities caused by basins are known to some extent (e.g., Vidale and Helmberger, 1988; Kawase and Aki, 1989; Olsen *et al.*, 1995), the actual separation between effects produced by source excitation and path effects remains uncertain. For example, Olsen *et al.* (1995) predict maximum ground velocity of 1.4 m/sec in the Los Angeles basin for a hypothetical magnitude 7.75 earthquake on the San Andreas fault based on a 3D model. They suggest that 6-sec strong motions would be amplified by over a factor of 5 in the basin, compared to a flat-layered model (1D). However, if we compare the Landers ($M = 7.2$) observation at Pasadena (PAS, Fig. 1) with the strongest observations in the Los Angeles basin (DOW) in displacement, we get an amplification factor of about 2. Since the high ratios predicted by Olsen *et al.* (1995) were apparently very localized, we probably should not be surprised not to have observed these features during the Lander's event. Moreover, the amplification numbers in the Olsen *et al.* (1995) simulation will remain somewhat uncertain, because their results depend strongly on the crustal structure between Los Angeles and the fault and relative seismic excitation of the upper layers.

The calculation of a propagating rupture embedded in a 3D model is a significant technological advancement, but there are still many advantages in methodologies that separate the various complexities into individual operators. Following this approach, we break down the problem into (a) *source excitation,* with various assumptions about rupture properties and depth excitation; (b) *path effects,* i.e., regional seismic propagation from the source elements to the site (Los Angeles); and (c) *site effects* caused by the basin structure. While source studies of recent earthquakes have contributed significantly to source excitation, the installation of the TERRAscope network has greatly improved our ability to under-

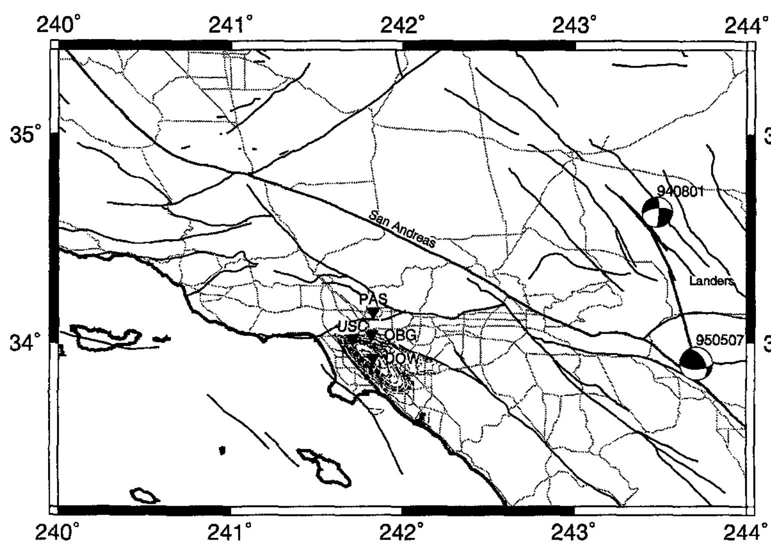

Figure 1. Map of southern California, displaying major faults, Los Angeles basin with seismic stations, two aftershocks, and the Landers fault rupture. The dashed light contours indicate the isosurface of the Los Angeles basin (from Yerkes *et al.*, 1965). OBG and DOW were triggered by the mainshock.

stand path effects, since the multitude of small events can be used to calibrate paths. For example, Zhu and Helmberger (1996) show that if one corrects the 355 events ($M > 3.5$) that have occurred since 1990 for mechanism and depth, the average decay of Love waves (3- to 8-sec periods) across TERRAscope is nearly the square root of distance ($r^{-0.55}$). Corrections are based on a particular 1D-layered model, [SoCal, Dreger and Helmberger (1991)] (Table 1). The top layer of this model is thick (5.5 km) and relatively fast (3.15 km/sec). Thus, it is obviously an average structure both vertically and horizontally. Its only justification is that it predicts synthetics fitting a large number of observations both in timing and waveform and provides a useful regional reference. The observations at soft-rock sites require some method of model localization that is addressed in this article. Our main objective is to develop a convenient method of predicting the motions at a soft-rock site based on observation or simulation at a hard-rock site.

The site response due to complex structure can be corrected by using a transfer function. For simple 1D models, analytical solutions are available for the transfer functions (e.g., Idriss and Seed, 1967). For a complex geologic structure, site transfer functions can be obtained by deconvolving the responses at hard-rock sites from those in the basin or soil conditions for events arriving from the same azimuth (Borcherdt *et al.,* 1975). The procedure is illustrated in Figure 2, which shows the transverse components of displacement obtained at the two TERRAscope stations PAS and USC for two Landers aftershocks: 940801 and 950507. The source parameters for these events are $M = 4.4$, depth = 10 km, strike = 0°, dip = 78°, and rake = 204° for event 940801 (Jones, 1995) and $M = 4.8$, depth = 13 km, strike = 331°, dip = 48°, and rake = 140° for event 950507 (H. K. Thio, personal comm.). Following the above approach, we can deconvolve the PAS (940801) record from the USC (940801) record and obtain a transfer function to predict the USC (950507) recording, which is given at the bottom of the figure. Generally, to stabilize the deconvolution, one needs to remove high frequencies; thus, the lightly filtered USC observation is included for direct comparison. The agreement is quite good, even though the aftershocks were very different in location and mechanism. Note that the 950507 event arrives at USC at a 45° angle to the basin, while the 940801 event arrives more nearly at a right angle. Thus the path of the 940507 event spends more time in the basin and appears to have a stronger coda accordingly. However, the peak amplitude and main features of the prediction are good and useful as a correction. The mainshock was recorded at PAS but not at USC, unfortunately. However, strong-motion data are available at Obregon Park (OBG) and Downey (DOW) for the 1992 Landers earthquake. As displayed in Figure 1, OBG is at the edge of the Los Angeles basin, and DOW is in the central part of the basin.

Ideally, we would need aftershock data at these sites to proceed, but lacking these recordings, we can generate synthetic motions and develop theoretical transfer functions.

Table 1
Southern California Crustal Model (SoCal)

Depth (km)	V_s (km/sec)	ρ (g/cm^3)
5.5	3.18	2.40
16.0	3.64	2.67
35.0	3.87	2.80
∞	4.50	3.00

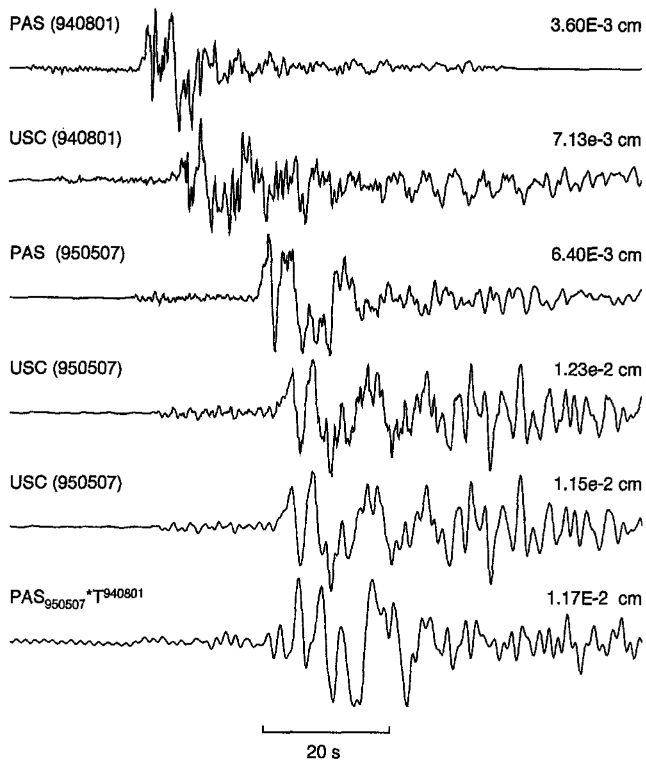

Figure 2. The tangential displacements observed at the TERRAscope stations PAS and USC for two aftershocks: 940801 and 950507. The slightly bandpassed (<1.0 Hz) and predicted displacements of USC for event 950507 are shown at the bottom. The prediction is made by convolving the recording at PAS (950507) with the transfer function.

The remainder of this article is devoted to this task along with a check against this small set of existing strong-motion data for the Landers earthquake.

Theoretical Transfer Functions and Modeling of Landers Event

The synthetics generated in this section involve a hybrid method introduced by Wen *et al.* (1994). This method interfaces the generalized ray technique (Helmberger, 1983) with a finite-difference routine that handles the soft-rock basin structure. A display of the geometric setup is given at the top of Figure 3, assuming the SoCal model. The 2D basin model is modified from Scrivner and Helmberger (1994) us-

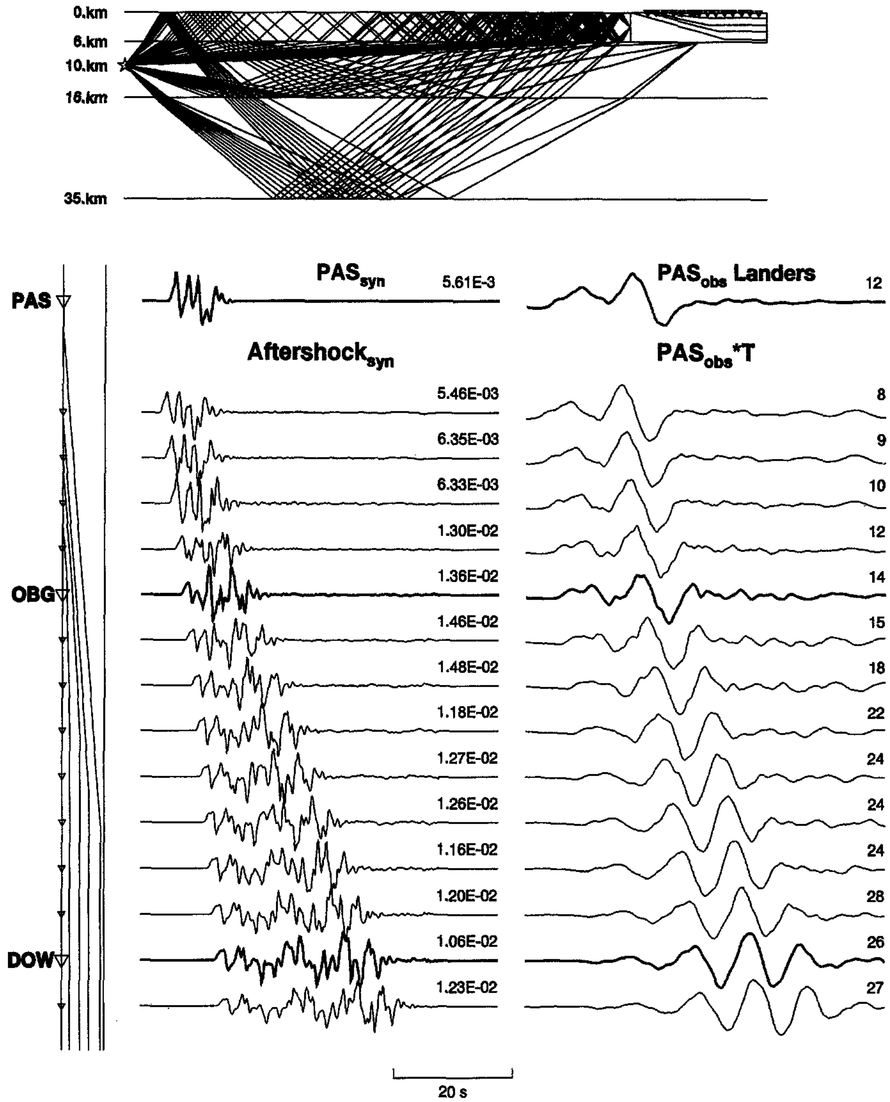

Figure 3. The SoCal model and associated ray paths are shown at the top of the figure followed by two columns of synthetics. Aftershock synthetics for event 940801 (left) start with a prediction at PAS (hard-rock site). Peak amplitudes in centimeters are given above each trace. Simulations of the mainshock are given on the right starting with the observation at Pasadena.

ing their seismic parameters but simplifying the structure for convenience. The synthetic at PAS for the aftershock 940801 is produced from the 1D model assuming the source parameters obtained by Jones (1995). Synthetics are given on the left for a theoretical line of stations along the basin profile. Locations (in distance) appropriate for OBG and DOW are highlighted. Note the rather complicated increase in waveform complexity and amplitude as we move into the basin. Theoretical transfer functions were obtained by deconvolving PAS from each of these synthetics. The observed displacement at PAS for the mainshock is given on the right. Convolving this response with the various transfer functions produces the column of mainshock predictions. Note that the amplitudes increase from 12 cm (peak motions) to 28 cm or about a factor of 2.

Output from this same setup for a different 1D model is presented in Figure 4. This model (Table 2) fits the observed PAS aftershock 940801 waveform much better than that for the standard SoCal model, as can be seen by overlay with Figure 2. However, the predicted mainshock synthetics are quite similar. The actual transfer functions used in Figure 4 for OBG and DOW are given in Figure 5. The transfer functions are not very impulsive since the two responses have a similar beginning, but with varying phases. The basin Love wave is quite apparent with its long periods.

Figure 6 displays a detailed comparison between the observed data and predictions made by these transfer functions. These strong-motion data were produced by the California Strong Motion Instrumentation Program, Division of Mines and Geology (CDMG) instruments (Shakal *et al.*,

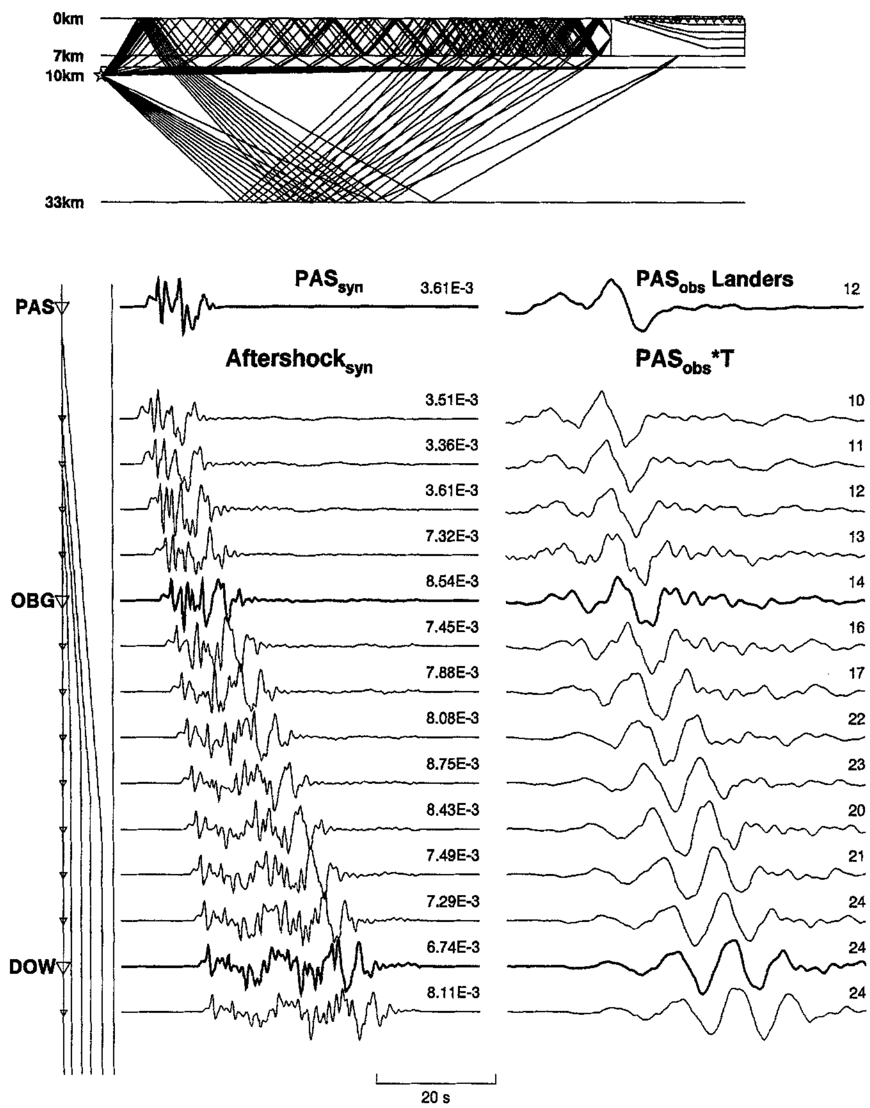

Figure 4. An alternate model (Table 2) and associated ray paths are shown at the top of the figure followed by two columns of synthetics. Aftershock synthetics (left) start with a prediction at PAS (hard-rock site). Peak amplitudes in centimeters are given above each trace. Simulations of the mainshock are given on the right starting with the observation at Pasadena. The synthetic at PAS for event 940801 fits the observation very well for this 1D model, as can been seen by comparing with the data in Figure 2.

Table 2
Crustal Model from Modeling PAS (940801)

Depth (km)	V_s (km/sec)	ρ (g/cm^3)
6.5	3.13	2.40
8.5	3.55	2.67
32.5	3.77	2.70
∞	4.10	3.00

1987). The sensors record acceleration with free periods of about 0.0395 sec and damping coefficients of around 0.59. The response is flat to about 10 Hz. The raw acceleration has been resampled to a rate of 50 samples per second and bandpass filtered with ramps from about 0.3 to 0.6 Hz and 23.0 to 25.0 Hz during CDMG processing. The integration into displacement is displayed in the top traces. The bottom four rows show the contributions associated with various crustal paths. The two rows at the bottom contain the responses produced by the reflections from the Moho: *SmS* and the surface reflection *sSmS.* These pulses are relatively short period and quite important in velocity or acceleration, but they contribute little to the rather long-period displacement. Thus, the waves trapped in the upper wave guide completely dominate the long-period (<0.2 Hz) displacement behavior. These features are also true at hard-rock sites as discussed by Helmberger *et al.* (1993). Since the paths controlling acceleration (>1 Hz) enter the basin at relatively steep angles, they are less likely to be trapped by the deep

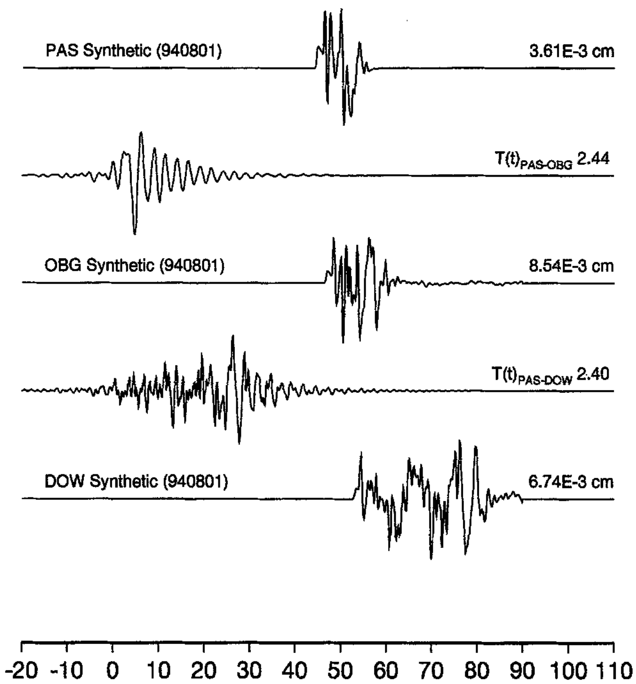

Figure 5. Illustration of constructing the transfer functions for two sites. The transfer functions are constructed by deconvolving the synthetic at PAS from the basin responses at OBG and DOW. Transfer functions are labeled as $T(t)$ with the numbers indicating the relative amplification.

basin structure. Thus, the 1D soil transfer functions (Idriss and Seed, 1967) are probably more appropriate for correcting these frequencies than the basin Green's functions, although complex shallow velocity structure remains a problem.

Discussion and Conclusion

The hybrid method and the transfer function concept introduced in the above analysis have many advantages. Foremost, since PAS has been recording both weak and strong motions for more than 50 years, these data can be used along with theoretical transfer functions to assess those existing strong motions in the Los Angeles basin as done for Landers. Second, as the basin arrays are installed (Hauksson *et al.,* 1995), we can use both observed and theoretical transfer functions to refine the ability to correct for responses at soft-rock sites.

In predicting motions for great earthquakes, we can begin by assuming a hard-rock site and obtain motions through simulation (Cohee *et al.,* 1991) or by using the empirical database (e.g., Joyner and Boore, 1988). Since directivity becomes particularly important at long periods, these effects can, again, be easily treated using 1D models. For example, the motions at PAS for the Landers mainshock are quite predictable from knowledge of the rupture, as discussed by Dreger (1994).

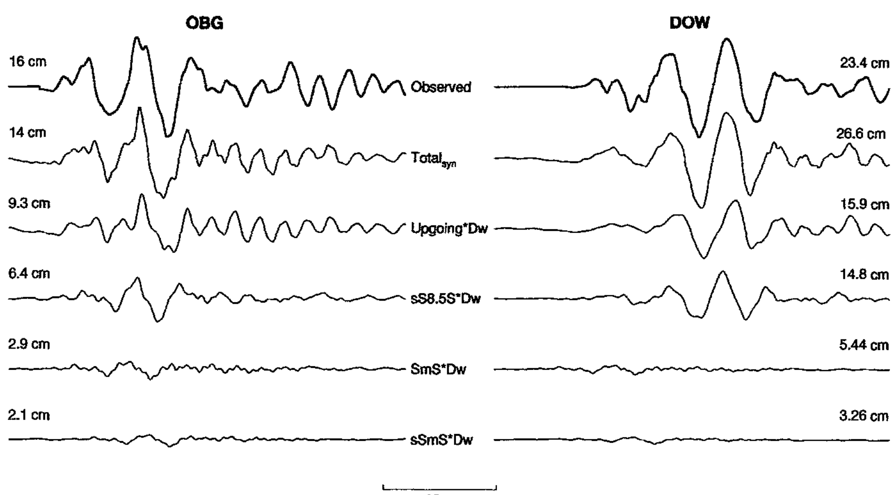

Figure 6. The basin responses at OBG and DOW due to the different types of incident energy. The top traces are the observed displacements. The basin responses due to incident *sSmS* (reflected from surface and turned back to surface by the Moho), *SmS* (downdoing and turned back by the Moho), *sS8.5S* (reflected from surface and turned back by an interface at 8.5 km depth), and direct upgoing wave are labeled as *sSmS, SmS, sS8.5S,* and Upgoing. Those responses are generated by convolving the transfer functions related to each incident group of rays with moment rate function, obtained by deconvolving the PAS aftershock from mainshock.

In conclusion, we have developed a convenient method for estimating basin effects based on transfer functions. The transfer function is the deconvolution of the hard-rock site (1D) synthetic from (2D) synthetics at the soft-rock site assuming a simple source. The soft-rock site response for a major event can then be obtained by convolving the transfer functions with the corresponding hard-rock site response. The prediction of responses in the Los Angeles basin for the 1992 Landers earthquake assuming the PAS record as a reference yields good agreement with observations (<0.3 Hz) in terms of amplitude and waveform. With improving knowledge about basin structure and computation advances, perhaps the shorter periods will also become predictable.

Acknowledgments

We thank Hiroo Kanamori for the use of his deconvolution code and Hiroo Kanamori, Kim Olsen, Lee Steck, and Craig Scrivner for their reviews. This work was funded by SCEC Contract Number 569933 and NSF Grant EAR-9416340. Contribution Number 5732, Division of Geological and Planetary Sciences, California Institute of Technology.

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Manuscript received 4 June 1996.